MODELLING OF THE ACTIVATION OF A STRETCH REFLEX IN VIEW OF IMPROVING THE MUSCULAR FORCE

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Abstract- **This paper presents a method to improve the muscular force for a patient's muscle during rehabilitation or training. The aim of this work is to formalise a stretch reflex called myotatic reflex by building an adequate model. This model is then used together with a muscle model to illustrate, through simulation, the efficiency and the feasibility of the method relatively to an isokinetic machine.**
***Keywords*- Mechanical stimulation, myotatic reflex, muscular force improvement, stretch reflex, gamma loop.**

I. INTRODUCTION

In the domain of medical training or rehabilitation, the muscular intensification is obtained by repetitive movements. These movements, which are defined by the practitioners or the trainers, are often performed with the help of isokinetic machines. In view of improving the performance of these machines, the paper presents a method to enhance the muscular intensification by using the stretch reflex [1].

After defining the muscle structure and the physiological phenomenon induced by the gamma loop, Section 2 proposes a model of the stretch reflex activation. A muscle model illustrating the effect of stretch reflex activation on the improvement of the muscular force is presented in Section 3. The feasibility of this model relatively to an isokinetic machine will be discussed and some simulation results are given for illustration.

II. STRETCH REFLEX ACTIVATION MODEL

A. Physiological definition of the gamma loop

The muscle structure (Fig. 1) includes the following elements:

- muscular fibers (called extrafusales fibers) of contractile nature which are controlled by the nervous system through alpha motor neuron axons,
- the neuromuscular spindle innerved by sensory endings, *Ia*/*II*, and by gamma motor neurons [1][2],
- the tendon which connects extrafusales fibers with the skeleton bone and which is connected to the nervous syste by the afferent fiber, *Ib*.

The Gamma Loop principle is rather simple. If the gamma motor neuron is activated, then this would increase the tension in the muscle spindle and, consequently, reinforce the activity in the *Ia* afferent fibbers. The increase in *Ia* activit increases the activity of the alpha motor neurons, which, in turn, causes the extrinsic muscle fibbers to contract.

The role of gamma motor neurons [1] is to prepare the movement of the muscle in the case of an unforeseen alert situation, in a way to comply with the mechanical structure of the muscle. Indeed, it allows the muscle to control its contraction during a rough stretching, facilitates the depolarisation of alpha motor neurons, and stresses the muscular reactive contraction. To increase the muscular performances of a subject, it is necessary to control the muscular activity (contraction) which is responsible for effort evolution and for the delivered power [2][3].

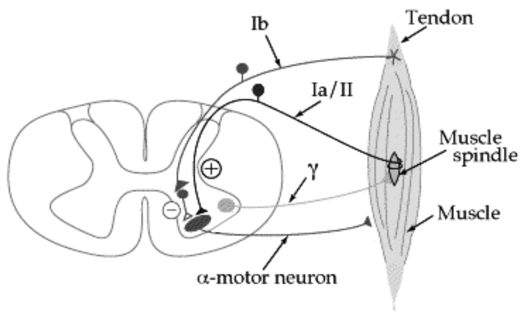

Fig. 1. Muscle morphology and gamma loop principle.

The aim of the work presented in this paper is to exploit the stretch reflex to improve the muscular intensification through the application of an external stimulation [1]. During a contraction, several abrupt stretches of the muscle are used to provide consecutive activations of the reflex. In this way, the muscle is solicited with supplementary contractions, which are added to the basic contraction, to increase the developed force. This technique has been applied to Isokinetic and Isometric movement types [1].

During an isokinetic movement which is realised with a predetermined constant velocity, it is possible to provoke the myotatic reflex in two different ways (Fig. 2):

- Stimulation by abrupt inversion of the movement direction (Fig. 2a);
- Stimulation by an abrupt advance of the movement in the original direction and then by an inversion of the movement direction (Fig. 2b).

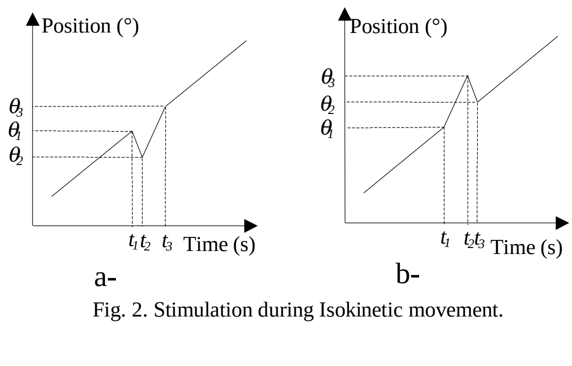

Fig. 2. Stimulation during Isokinetic movement.

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In the isometric movement, the length of the muscle is maintained constant while the subject produces a muscular effort [4]. Here again, the myotatic reflex can be provoked in two different ways (Fig. 3):

- Stimulation by an abrupt change of the position in the same direction of the effort, then return back to the initial position (Fig. 3a);
- Stimulation by an abrupt change of the position in the opposite sense of the effort, then return to the initial position (Fig. 3b).

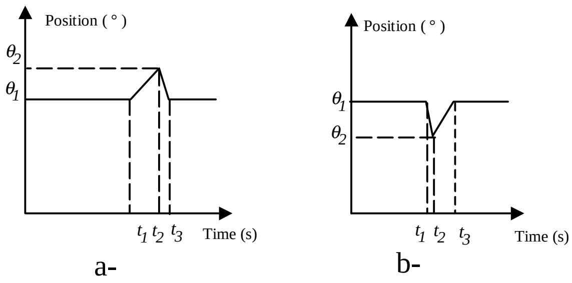


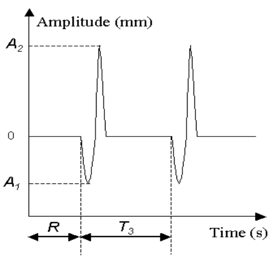
Fig. 3. Stimulation during Isometric movement.

Based on the above definitions, a stretch reflex stimulation model will be proposed in view of evaluating, through simulation, the effect of this technique on the muscle.

B. Stretch reflex activation

To provoke the stretch reflex, it is necessary to stimulate the muscle with a sequence of impulses during the movement; these impulses should be periodic, of adjustable period, and applicable to the two scenarios presented above.

For example, a negative impulse followed by a positive impulse should be applied in the case of the abrupt inversion of the movement direction during Isokinetic mode (Fig. 4). The amplitude and the duration of each impulse are to be adjusted according to the frequency of application of the consecutive stimulations. The equation of the impulse signal $\Omega(t)$ is also given in Fig. 4, where "*" represents the convolution product, T_1 (respectively, T_2) is the duration o the first (respectively, second) impulse, T_3 is the global stimulation period, and R is the time delay.



$$\Omega(t) = \begin{cases} \left[(I_1 + I_2) * \sum \delta(t - nT_3 - \frac{1}{R}) \right] \\ \text{with} \\ I_1 = A_1 \sin(\frac{2\pi}{T_1} t).rect_1 \\ I_2 = A_2 \sin(\frac{2\pi}{T_2} t).rect_2 * \delta(t - 2\frac{1}{T_1}) \end{cases}$$

Fig. 4. Gamma impulse and the corresponding equation

The mechanical activation of the stretch reflex requires the satisfaction of a number of physiological constraints in view of activating the reflex. For example, it is necessary to use a 1 to 3 degrees articulation angle for the knee, and a 5 to 100 Hz activation frequency.

C. Feasibility on an isokinetic machine

An isokinetic machine, developed by our research group in association with the company Myosoft (Bellegarde-France) [4][5], was chosen as a support for the validation of the proposed method. This machine, called Multi-Iso, is used for the muscular training and rehabilitation of the quadriceps and the hamstrings. It reinforces the muscular intensification by performing a series of repetitive movements.

During a training session, the basic muscular contraction ca realise either a concentric, an eccentric, or an isometric action [6][5]. The implemented control laws provide classical training possibilities to achieve muscular intensification in a natural way [4]. Furthermore, the muscular performance of a subject depends on the muscular activity (contraction). This contraction can be increased by the mechanical stimulation of the stretch reflex. Fig. 5 gives the block diagram of the control system used for the machine together with the stretch reflex activation model.

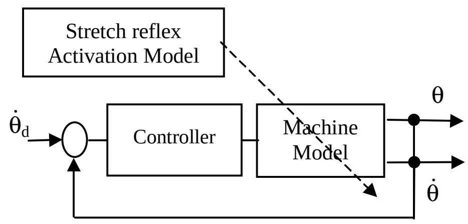


Fig.5. Stretch reflex and Multi-Iso control model

Having identified the parameters of the machine model, a simulation phase was used to study the feasibility of the reflex activation relatively to the machine dynamics. The simulation results for isometric and isokinetic modes at 60°/s, has shown that the machine dynamics can react to stimulation amplitudes ranging from 0.5 to 5 degrees with a maximal frequency of 50Hz. Thus the machine partially satisfies the imposed physiological constraints. The use of higher stimulation frequencies requires a slight modification in the mechanical structure and in the motor system of the machine. The next section presents an adequate muscle model to illustrate the efficiency of the method during a muscular contraction.

III. MUSCLE MODEL AND SIMULATION RESULTS

Several muscle models have been proposed in the literature [3,7,8, 9,10,11,12]. The first mechanical model of the muscle, known as Hill's model, was finalised in 1924 by H. Gasser and H. Hill [3]. This model describes the set muscle/tendon using a contractile element, CE, and two springs, SEE and PE (Fig. 6). SEE is connected in series with CE to represent the elasticity of the tendon, SEE, whereas the passive element, PE, is connected in parallel to represent the elasticity of the muscle. In this model, F_{CE}, which represents the active force of the contractile element, depends on the muscle fibber length, l^M, and the state of activation of the muscle fibbers. F_{PE} represents the passive force of the elastic element, and F^M is the sum of the passive and the active forces.

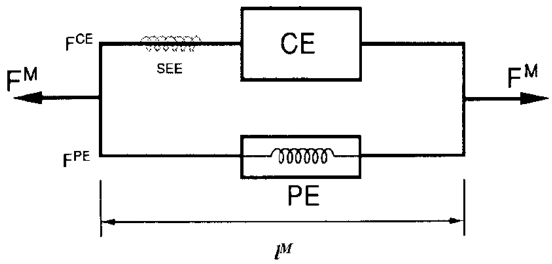
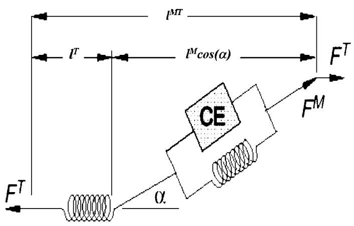


Fig. 6. Hill-type model for contraction dynamics of muscle.

The Hill's model was generalised by Zajac, by taking the angle between the muscle and the tendon into account and using a supplementary spring, connected in series with a system equivalent to Hill's model (Fig. 7). Thus, the elastic element, SEE, of Hill's model is separated here into two elements to be able to represent the steepness of each of the elastic elements of the model, the muscle and the tendon.



l^T: tendon length,
l^{MT}: muscle/tendon length,
F^T: applied force on the tendon,
α : Angle between the muscle and the tendon.

Fig. 7. Zajac's muscle model.

A refined version of Zajac's model, taking the non-linear dynamics of the muscle into consideration [2], was also proposed by Brown & al [7] [8]. We propose a re-formalisation of this refined model by highlighting the physical equations to deduce the muscular force required for the evaluation of stretch reflex effect on isokinetic machines.

Denote by M the muscular mass with two forces, F^M and F^T, connected with its extremities, and γ the muscular acceleration. The proposed refined Zajac's model is rewritten in terms of the fundamental dynamics law as follows:

$$\sum F_{ext} = \sum F_{\text{int}}$$

$$F^M - F^T = M \cdot \gamma$$

According to Fig. 7, one can write:

$$(F_{PE} + F_{CE}) - F^T = M \cdot \gamma$$

with : $\tilde{F}_{PE} = \tilde{F}_{PE1} + \tilde{F}_{PE2} \cdot \tilde{A}f$

and $\tilde{F}_{CE} = \tilde{F}_L \cdot \tilde{F}_V \cdot \tilde{A}f$

where "~" indicates a normalised variable, γ is the muscular acceleration, $\tilde{F}_{PE1}$ is the passive elasticity designating the effort evolution of a muscle during stretching, $\tilde{F}_{PE2}$ is a passive elasticity designating the effort evolution during the shortening of a muscle, *Af* is the activation frequency which depends on $\tilde{F}_{PE2}$, $\tilde{F}_L$ is the tetanic isometric force-length relationship which is a function of the muscle length, and $\tilde{F}_V$ is the tetanic force-velocity relationship.

Figure 8 represents the force produced by the muscle model, F_l, where the muscle length, l^{MT}, varies linearly as a function of the knee angle, θ.

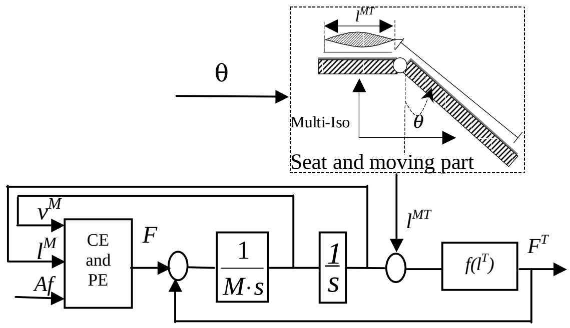


Fig. 8. Block diagram of the proposed muscle model

The stimulation efficiency of the stretch reflex during a muscular contraction will be illustrated by estimating the increase of the force generated by the reflex contractions related to the successive stimulations. The simulation set-up (Fig. 11) integrates: the muscle model [1], the Stretch reflex activation model generating the stimuli during the movement [1], and a model of the isokinetic machine together with the adequate control laws for isokinetic and isometric movements.

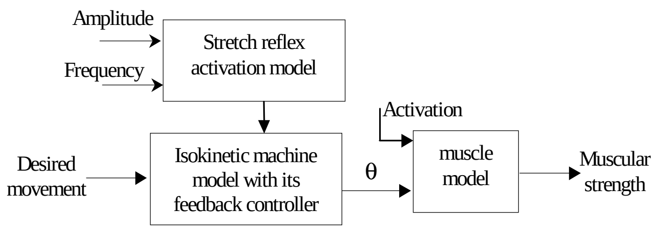


Fig. 9. Block diagram of the simulation set-up

The simulation results depicted in Fig. 12 and 13 illustrate the influence of the stretch reflex stimulation on the force developed by the muscle in isokinetic and isometric modes. The results are compared with those obtained using the same training modes, but without the activation of the stretch reflex loop stimulation. This figures show an improvement of the muscular force for various stimulation frequencies ranging from 5 to 50Hz and for amplitudes from 1 to 5 degrees.

IV. Conclusion

This paper concerns the formalisation of the neuromuscular myotatic reflex in view of improving the muscular force. The resulting stretch reflex activation model was adapted to an isokinetic machine for lower limbs training. By using an adequate muscle model, simulation results illustrate the efficiency of this method for improving the muscular force in the case of isokinetic and isometric movements. Current research is directed at experimentally validating the method on the isokinetic machine. It's also important to evaluate the

pertinence of the resulting force gain compared to classical training methods. Another work in progress is related to the refinement of the muscle model by considering parameters related to the muscle fatigue.

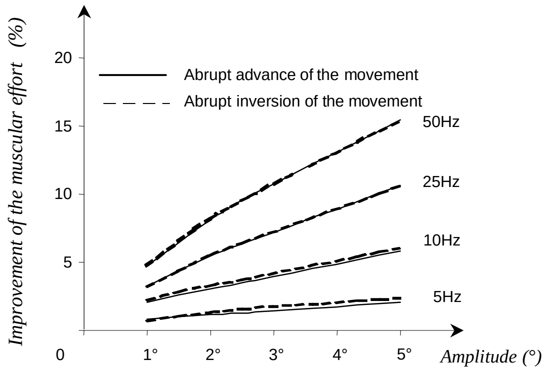


Fig. 10. Increase of muscular force during Isokinetic movement.

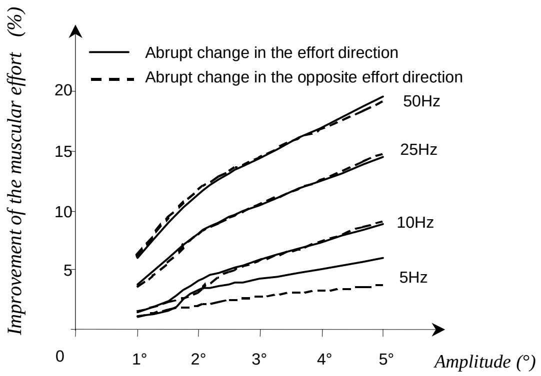


Fig. 11. Increase of muscular force during Isomeric movement

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